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Comparison of Lower Extremity Kinematics and Hip Muscle Activation During Rehabilitation Tasks Between Sexes

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Context: Closed kinetic chain exercises are an integral part of rehabilitation programs after lower extremity injury. Sex differences in lower extremity kinematics have been reported during landing and cutting; however, less is known about sex differences in movement patterns and activation of the hip musculature during common lower extremity rehabilitation exercises.

Objective: To determine whether lower extremity kinematics and muscle activation levels differ between sexes during closed kinetic chain rehabilitation exercises.

Design: Cross-sectional with 1 between-subjects factor (sex) and 1 within-subjects factor (exercise).

Setting: Research laboratory.

Patients or Other Participants: Participants included 21 women (age = 23 ± 5.8 years, height = 167.6 ± 5.1 cm, mass = 63.7 ± 5.9 kg) and 21 men (age = 23 ± 4.0 years, height = 181.4 ± 7.4 cm, mass = 85.6 ± 16.5 kg).

Intervention(s): In 1 testing session, participants performed 3 trials each of single-leg squat, lunge, and step-up-and-over exercises.

Main Outcome Measure(s): We recorded the peak joint angles (degrees) of knee flexion and valgus and hip flexion, extension, adduction, and external rotation for each exercise. We also recorded the electromyographic activity of the gluteus maximus, rectus femoris, adductor longus, and bilateral gluteus medius muscles for the concentric and eccentric phases of each exercise.

Results: Peak knee flexion angles were smaller and peak hip extension angles were larger for women than for men across all tasks. Peak hip flexion angles during the single-leg squat were smaller for women than for men. Mean root-mean-square amplitudes for the gluteus maximus and rectus femoris muscles in both the concentric and eccentric phases of the 3 exercises were greater for women than for men.

Conclusions: Sex differences were observed in sagittal-plane movement patterns during the rehabilitation exercises. Because of the sex differences observed in our study, future researchers need to compare the findings for injured participants by sex to garner a better representation of altered kinematic angles and muscle activation levels due to injury.

Key Words: electromyography, rehabilitation exercises

Key Points

- Women had smaller degrees of knee flexion and larger degrees of hip extension angles when compared with men across all exercises.
- Men had larger degrees of hip flexion during the single-leg squat compared with women.
- Women had higher activation levels of the rectus femoris and gluteus maximus muscles compared with men across all exercises.

Closed kinetic chain (CKC) exercises are integral for rehabilitation programs after lower extremity injury. Much research has been focused on the activation levels of the quadriceps and hamstrings muscle groups in identifying rehabilitation exercises for injuries to the knee joint.[1–8] More recent investigations have highlighted the importance of the muscles acting upon the hip joint, specifically the hip abductor muscles, in preventing and treating distal lower extremity injuries.[9–13] Particularly, altered activation levels of the gluteus medius muscle have been purported to result in increased frontal-plane motion at the hip joint during weight bearing, producing greater degrees of knee valgus angle.[14] This position has been cited as a possible cause for lower extremity injury.[15] As a result, activation levels of the gluteus medius muscle during lower extremity rehabilitation exercises have received considerable attention as investigators have tried to identify appropriate treatment strategies.[14,16–20] Although numerous researchers have studied the function of the gluteus medius muscle, limited information exists regarding the influence of the activation levels of other muscles acting upon the hip joint. In addition, little has been documented regarding the influence of muscle function on movement patterns of the hip joint itself during functional exercises. To better identify alterations in hip function after lower extremity injury, descriptions of movement patterns and muscle activation levels in healthy individuals are required.

Alterations in lower extremity muscle activation patterns have been documented for individuals with different lower extremity disorders, specifically anterior knee pain,[9] chronic ankle instability,[13] and severe ankle sprains.[21] Delays in muscle onset latency and shorter overall duration of muscle activity have been documented for the gluteus medius muscle during stair climbing in patients with anterior knee pain[9] and during inversion ankle perturbations for patients with chronic ankle instability.[13] Additionally, delays in muscle onset and reductions in muscle activity duration for the gluteus maximus muscle have been observed during hip extension movements in patients after severe ankle sprain.[21] However, none of these investigators documented lower extremity kinematic movement patterns in accordance with the changes in muscle activity. Therefore, it cannot be determined whether the alterations in muscle activation patterns would result in alterations in lower extremity movement patterns during the tasks.

Lower extremity kinematic movement patterns have been documented during jumping and landing, squatting, and cutting exercises in healthy populations.[14,22–25] Females have been shown to exhibit greater knee valgus[23,24] and knee extension[22] angles during landing when compared with males. Pollard et al[26] reported that mean hip internal rotation and extension angles during a side-step cutting task were greater for women than for men. Zeller et al[14] also observed sex differences in frontal-plane and transverse-plane hip motion during a single-leg squat task and reported that women demonstrated much greater hip adduction and external rotation angles when compared with men. Although kinematic movement patterns have been examined during more sport-specific functional exercises in healthy people and differences between sexes have been documented, few examiners have studied movement patterns during other CKC lower extremity rehabilitation exercises. An understanding of movement patterns and activation levels of the surrounding musculature during rehabilitation exercises would allow clinicians to better prescribe these exercises based upon the muscular demands.

Because normative information regarding lower extremity kinematics and activation levels of the hip musculature during CKC rehabilitation exercises is lacking, documenting the movement patterns of an uninjured population during these exercises is important for future identification of abnormalities in patients with lower extremity injury. Because sex differences in these variables have been demonstrated during the performance of lower extremity functional tasks in previous studies, comparing males and females during CKC rehabilitation exercises is warranted. The purpose of our study was to determine whether lower extremity 3-dimensional kinematics and hip muscle electromyographic (EMG) activation differ between men and women. For the kinematic measures, we hypothesized that women would demonstrate greater peak hip adduction and knee valgus angles and smaller peak knee flexion angles during all tasks when compared with men. For the EMG measures, we hypothesized that women would demonstrate lower mean muscle activation levels of the dominant-limb gluteus medius muscle and higher mean muscle activation levels of the rectus femoris muscle when compared with men during all tasks.

METHODS

Participants

The sample size required to detect differences was determined using statistical software (nQuery Advisor; Statistical Solutions, Saugus, MA). Effect size was based on previous findings for mean difference (Δ) and common SD (σ) between men and women in hip flexion during performance of a single-leg squat ($\Delta = 9°$ and $\sigma = 8.2$).[14] The results of a 2-tailed *t* test for independent samples with the α set at .05 revealed that a sample size of 36 (18 per group) was needed to achieve 90% power. Based on these results, we recruited 44 participants (22 men and 22 women) aged 18 to 40 years to participate in our study. We included volunteers if they had no history of major lower extremity injury or surgery in either leg and were able to perform the 3 functional tasks being evaluated. Participants who reported histories of minor sprains or strains or of chronic conditions, such as tendinitis, were included if they were asymptomatic at the time of the study. The dominant limb was used for all testing. Leg dominance was determined by asking each participant with which leg he or she would kick a soccer ball. All participants read and signed a consent form, and the study was approved by the university's institutional review board.

Instrumentation

Three-Dimensional Kinematics. Three-dimensional joint kinematics of the hip and knee were collected using Flock of Birds electromagnetic sensors (Ascension Technology Corporation, Burlington, VT) and Motion Monitor software (Innovative Sports Training Inc, Chicago, IL). Electromagnetic sensors were placed on the sacrum, the lateral thigh above the lateral femoral condyle, and the tibial tubercle of the dominant limb of each participant and secured with double-sided tape and Cover-Roll (Beiersdorf-Jobst Inc, Charlotte, NC). Cardan angles of the hip and knee were calculated using the definitions of joint coordinate systems recommended by the International Society of Biomechanics.[27] Hip joint center was estimated using a method described by Leardini et al.[28] Calculations were based on data collected as participants moved the hip into a series of 10 static positions, which represented movements about the 3 axes. Kinematic data were sampled at a rate of 103 Hz.

Electromyographic Data. A 16-lead EMG system (Run Technologies, Mission Viejo, CA) was used to record muscle activity. A Myopac transmitter belt unit (Run Technologies) was worn by each participant during data collection and was used to transmit raw EMG data via a fiber-optic cable to its receiver unit. Unit specifications include an amplifier gain of 2000 Hz, an input impedance of 1 MΩ, and a common mode rejection ratio of 90 dB. Muscle activation of the dominant-limb's gluteus maximus, rectus femoris, and adductor longus muscles; the dominant-limb's gluteus medius muscle; and the nondominant-limb's gluteus medius muscle were collected for each participant using bipolar Ag-AgCl surface electrodes (Therapeutics Unlimited, Inc, Iowa City, IA) measuring 5 mm in diameter with a center-to-center distance of approximately 2.0 cm. Before electrode placement, the skin was prepared by dry-shaving the area, abrading the area with sandpaper, and cleansing it with alcohol to reduce impedance. Electrodes were placed in parallel arrangement over the muscle belly for each muscle as described by Cram et al,[29] and they were attached using Cover-Roll. To determine accurate electrode placement, participants were instructed to contract each muscle being tested while EMG activity was observed using the oscilloscope. The EMG data were sampled at 1339 Hz and synchronized with the kinematic data using Motion Monitor software. The unique frequencies were used to reduce distortion of the EMG signal caused by the 100-Hz direct current pulse that the electromagnetic transmitter generated.

Procedures

All data were collected at the Musculoskeletal Laboratory. Each participant reported to the laboratory for 1 testing session that lasted approximately 1 hour. A member of the research team (M.K.D.) demonstrated and taught each participant the proper technique and procedures for the single-leg squat, lunge, and step-up-and-over tasks. Each participant was allowed to practice until he or she felt confident in performing all 3 tasks. Before testing, each participant performed a 5-minute warm-up on an exercise bicycle, then a lower extremity flexibility program targeting the hip flexors, hamstrings, quadriceps, and hip adductors. Next, surface electrodes were applied to the 5 muscles as described.

After electrode placement, each participant performed 3 maximal voluntary isometric contractions (MVICs) for each muscle. Each trial lasted 3 seconds. To prevent fatigue, the participant rested for 30 seconds between trials and for 2 minutes between muscles. For the dominant-limb's gluteus maximus, he or she stood and leaned against a box for support. A strap was placed around the distal one-third of the thigh. The participant was instructed to flex the knee to 90° and push the thigh posteriorly against the strap, attempting to extend the thigh. For the rectus femoris, he or she was seated on the edge of a table with a strap around the distal one-third of the shank. The participant was instructed to push against the strap, attempting to extend the knee. For the adductor longus, each participant stood and pushed the foot of the dominant leg against the nondominant leg. For the gluteus medius, he or she stood facing a stationary pole, and a strap was placed around both feet. The participant was instructed to push out against the strap with the dominant leg to activate the gluteus medius, keeping the toes pointed forward while standing on the nondominant leg. Each participant was allowed to stabilize by holding onto the pole. This was repeated using the nondominant leg as the pushing leg for activation of its gluteus medius.

After collection of the MVICs, the participant was instrumented with the Flock of Birds sensors as described. When sensors were digitized, a static file was taken to determine resting angles of the hip, knee, and ankle joints to use for comparison. Next, the participant performed 3 trials each of the single-leg squat, lunge, and step-up-and-over exercises, resting for 30 seconds between trials and for 2 minutes between exercises to prevent fatigue.[30] Exercise order was randomized among participants using a random number sequence.

Single-Leg Squat. Participants were instructed to stand on their dominant legs with their hands crossed over their chests (Figure 1). Their nondominant legs were held in approximately 45° of knee flexion, and participants were instructed not to contact their nondominant legs with their dominant-stance legs at any time during performance of the activity. They were instructed to squat down as far as possible and return to single-leg stance without losing their balance. We did not control the distance through which each participant squatted, as we believed it better represented a clinical setting in which normal interparticipant variability would exist. We have begun using this method to study patients for whom meeting a specific range of motion during the performance of the exercise is difficult. If a participant touched the foot to the floor or made contact with the nondominant leg, the data were discarded, and the trial was repeated.

Lunge. The distance each participant traveled during the lunge was equal to leg length, as determined by measuring from the anterior-superior iliac spine to the medial malleolus of the tibia. Each participant was instructed to step out to this position using the dominant leg, lunge down as far as possible, return to full knee extension of the lunge leg, and return to the starting position (Figure 2). If a participant did not reach the full lunge distance, the data were discarded, and the trial was repeated.

Step Up and Over. Each participant stood next to an 8-in (20.32-cm)-high box on the platform (Figure 3). He or she was instructed to step up onto the box with the dominant leg, swing the nondominant leg up and over the box, step off the box with the dominant leg, and come to a stance on the platform. If a participant did not step over the box in 1 motion, the data were discarded, and the trial was repeated.

Data Processing and Analysis

Raw kinematic data were smoothed using a fourth-order, low-pass filter with a cutoff frequency of 5 Hz in the Datapac software (Run Technologies). Onset of each activity was determined when knee flexion angle rose 3 SDs above baseline and remained there for at least 50 milliseconds. Offset of each activity was determined when knee flexion angle dropped below 3 SDs above baseline and remained there for at least 50 milliseconds. Onset and offset of each activity was used to demarcate the phases for EMG data analysis.

For EMG data collected during MVIC testing, raw signals obtained during the 3-second trials were band-pass–filtered from 20 to 500 milliseconds and full-wave–rectified using the Datapac software. Each trial was analyzed by dividing the data into 500-millisecond windows, each overlapping by 100 milliseconds. The mean amplitude for each 500-millisecond window of each trial was acquired, and the highest mean amplitude for each trial was obtained. The peak mean amplitude of the 3 trials for each muscle was used for normalization.

For EMG data obtained during the 3 exercises, raw EMG signals were band-pass–filtered at 20 to 500 Hz, stored on a personal computer, and analyzed using the Datapac software. To determine the appropriate data-smoothing boundaries, the fidelity of the muscle amplitude after signal smoothing was evaluated using time constants from 5 to 50 milliseconds at 5-millisecond increments.

Figure 1. Single-leg squat exercise. A, The participant stands on her dominant leg and holds her nondominant leg in approximately 45° of knee flexion without allowing the legs to contact each other. B, She squats as far as possible before returning to the single-leg stance without losing her balance.

Based on the results of this analysis, filtered EMG signals were processed using root-mean-square (RMS) smoothing with a 20-millisecond time constant. Data were normalized to 100% of MVIC to allow for comparison among participants.

For EMG data analysis, the 3 exercises were divided into 2 phases: concentric and eccentric. Three trials of each task were recorded, analyzed, and averaged for statistical analysis. *Eccentric single-leg squat* was defined as the time from onset of activity to maximum knee flexion of the squat leg, and *concentric single-leg squat* was defined as the time from maximum knee flexion of the squat leg to offset of activity. *Eccentric lunge* was defined as the time from onset of activity to maximum knee flexion of the lunge leg in the descent phase of the lunge, and *concentric lunge* was defined as maximum knee flexion of the lunge leg in the descent phase to offset of activity. *Eccentric step up and over* was defined as maximum knee extension of the step-up leg to offset of activity, and *concentric step up and over* was defined as the time from onset of activity to maximum knee extension of the step-up leg. We were not interested in comparing the phases of activity; therefore, we performed separate analyses for each phase of each muscle for the 3 exercises. The dependent variables were average RMS amplitude represented as percentage of MVIC for each phase of the 5 muscles during each exercise (concentric and eccentric phases of the gluteus maximus, concentric and eccentric phases of the rectus femoris, concentric and eccentric phases of the adductor longus, concentric and eccentric phases of the dominant-limb's gluteus medius, and concentric and eccentric phases of the nondominant-limb's gluteus medius).

For the kinematic data analysis, peak knee and hip joint angles were determined throughout the entire exercise for each of the cardinal planes. The average of the peak joint angles obtained for each plane for the 3 trials for each exercise was used for statistical analysis. The dependent variables were peak knee flexion, peak knee valgus, peak hip flexion, peak hip extension, peak hip adduction, and peak hip external rotation angles for each exercise.

For each dependent variable, separate 2×3 repeated-measures analyses of variance were conducted. The independent variables were sex (male, female) and task (lunge, single-leg squat, step up and over). Post hoc Bonferroni comparisons were performed for all significant findings. The α level was set a priori at .05.

RESULTS

Of the 44 participants in our study, data for 2 participants had to be discarded because of data collection errors; therefore, data from 42 participants (21 women [age = 23 ± 5.8 years, height = 167.6 ± 5.1 cm, mass = 63.7 ± 5.9 kg] and 21 men [age = 23 ± 4 years, height = 181.4 ± 7.4 cm, mass = 85.6 ± 16.5 kg]) were included in the final analysis. Average height and mass were greater for the male than for the female participants ($P < .05$).

Three-Dimensional Kinematics

Means and SDs of peak angles for all kinematic variables for both men and women while performing the 3 exercises are shown in Table 1.

Knee Flexion. We found a main effect for sex ($F_{1,2} = 5.47$, $P = .02$). Peak knee flexion angles were smaller in

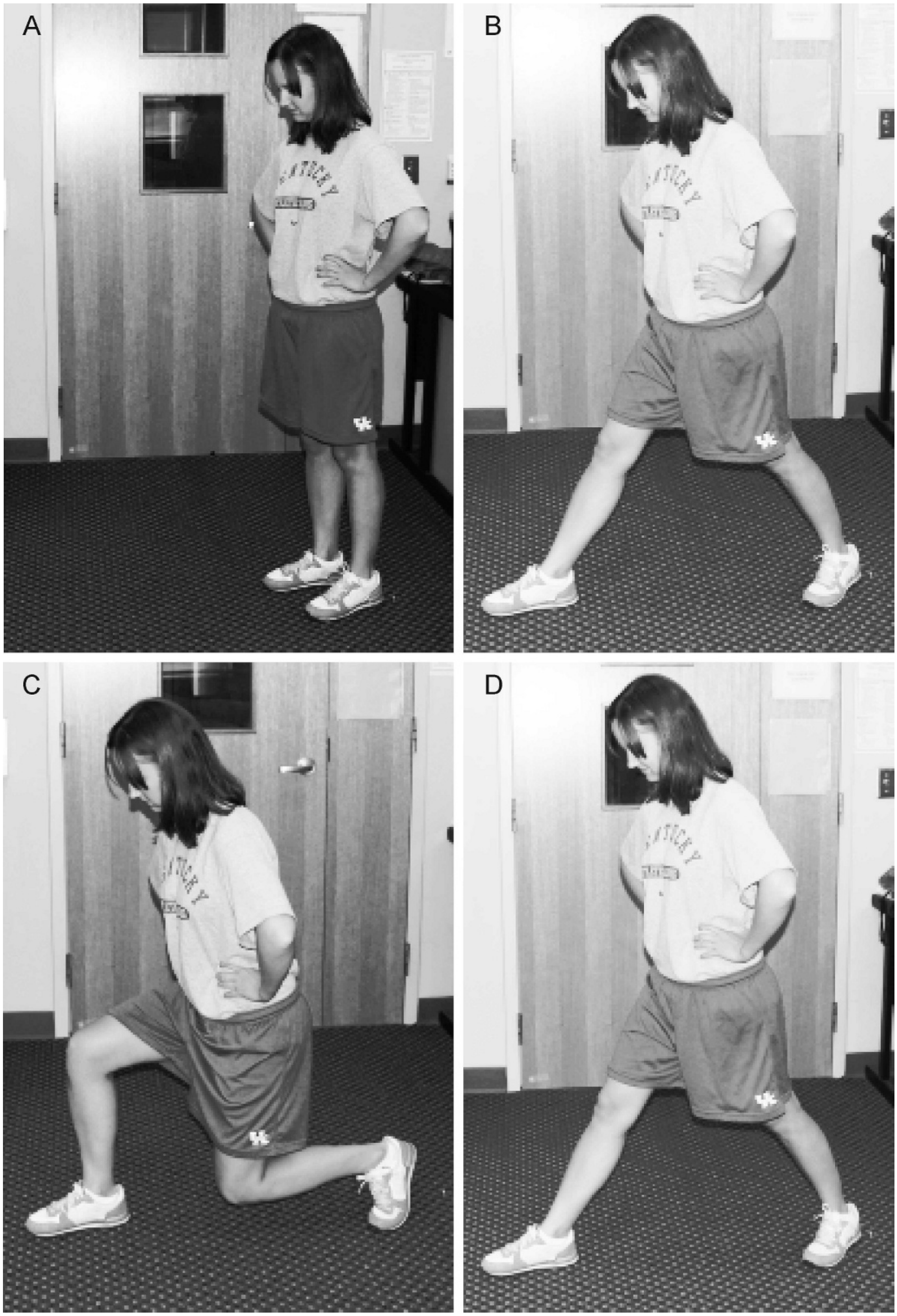

Figure 2. Lunge exercise. A, Starting position. B, The participant steps out using the dominant leg. C, She lunges down as far as possible. D, She returns to the full knee extension of the lunge leg.

women (74.7° ± 13.9°) than in men (79.2° ± 12.9°) across all tasks. We did not find a sex-by-task interaction ($F_{1,2}$ = 1.01, P = .37).

Knee Valgus. We found no differences between sexes for peak knee valgus angles during any of the exercises ($F_{1,2}$ = 0.009, P = .92). We found a sex-by-task interaction ($F_{1,2}$ = 3.9, P = .03). Post hoc testing revealed that peak knee valgus angles were smaller for men during the single-leg squat than during the step-up-and-over exercise ($F_{1,2}$ = 2.118, P = .04).

Hip Flexion. We did not find a difference between sexes ($F_{1,2}$ = 2.03, P = .16). However, we found a sex-by-task

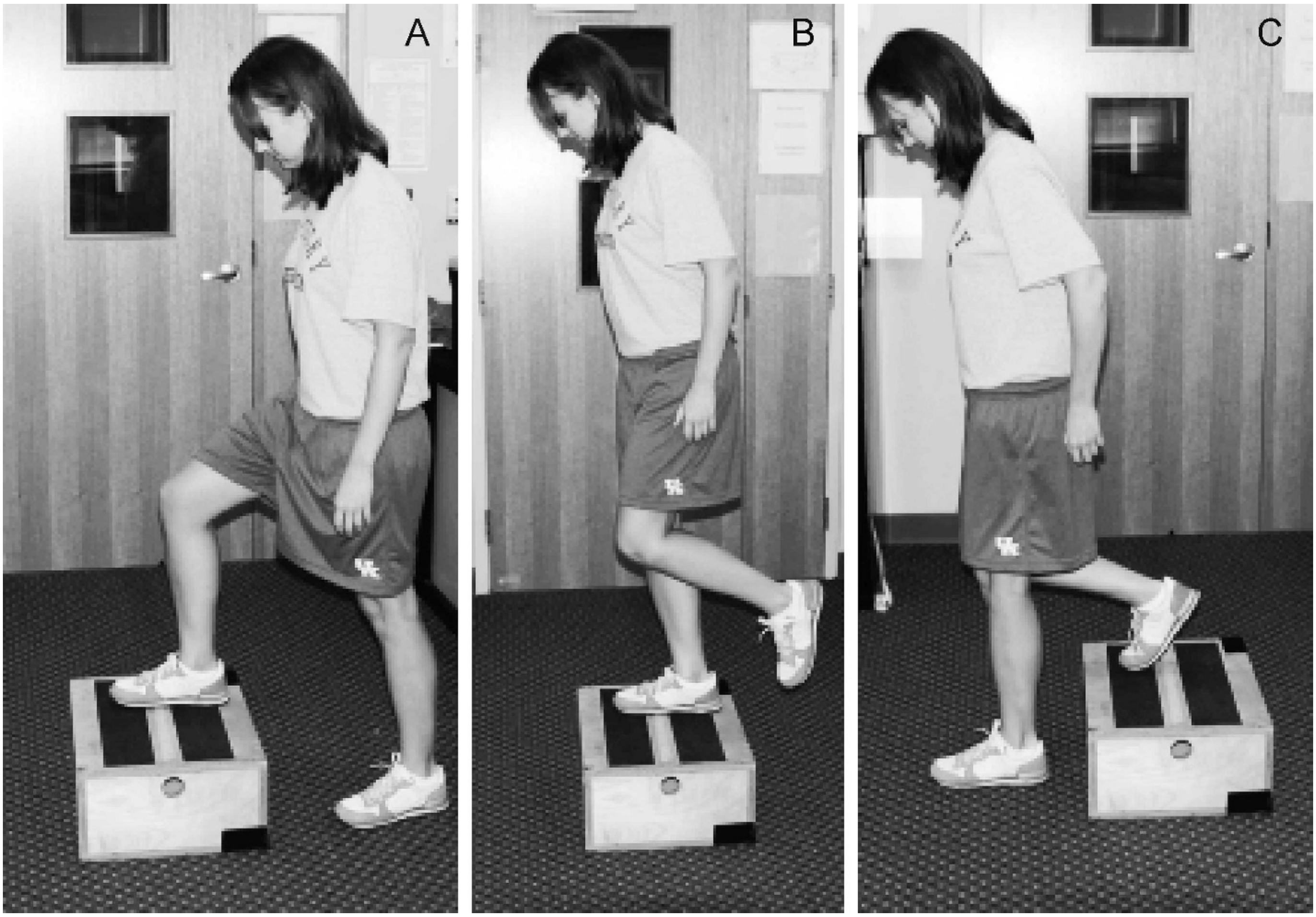

Figure 3. Step-up-and-over exercise. A, The participant steps up onto an 8-in (20.32-cm)-high box with the dominant leg. B, She steps over the box with the nondominant leg. C, She steps off the box with the dominant leg.

interaction ($F_{1,2} = 2.95$, $P = .06$). Post hoc testing revealed that peak hip flexion angles were smaller during the single-leg squat in women than in men ($P = .05$).

Hip Extension. We found a main effect for sex ($F_{1,2} = 11.9$, $P = .001$). Peak hip extension angles were greater in women (10.1° ± 7.2°) than in men (5.02° ± 5.6°) across all tasks. We did not find a sex-by-task interaction ($F_{1,2} = 2.1$, $P = .13$).

Hip Adduction. We did not find differences between sexes for peak hip adduction angles during any of the exercises ($F_{1,2} = 3.6$, $P = .07$). In addition, we did not find a sex-by-task interaction ($F_{1,2} = 0.13$, $P = .9$).

Hip External Rotation. We did not find differences between sexes for peak hip external rotation angles during any of the exercises ($F_{1,2} = 0.002$, $P = .96$). We also did not find a sex-by-task interaction ($F_{1,2} = 0.9$, $P = .41$).

Mean EMG Amplitude (Percentage of MVIC)

Means and SDs for the average RMS amplitudes for the eccentric and concentric phases of the 5 muscles during the 3 exercises for men and women are shown in Tables 2 and 3, respectively.

Table 1. Peak Range of Motion During Exercise (Mean ± SD)

	Exercise						Grand Mean for All Exercises, °	
	Single-Leg Squat, °		Lunge, °		Step Up and Over, °			
Kinematic Angle	Men	Women	Men	Women	Men	Women	Men	Women
Peak knee flexion	66.8 ± 9.70	60.0 ± 13.3	87.5 ± 11.2	82.3 ± 6.10	83.3 ± 6.70	82.5 ± 6.8	79.2 ± 12.9	74.7 ± 13.9[a]
Peak knee valgus	14.1 ± 8.80	12.4 ± 9.10	13.30 ± 7.3	12.9 ± 8.70	12.2 ± 7.80	12.9 ± 7.5	13.2 ± 7.9	13 ± 8.3
Peak hip adduction	18.3 ± 10.7	22.4 ± 8.30	9.90 ± 6.20	13.3 ± 7.70	13.0 ± 5.00	17.4 ± 6.4	13.7 ± 8.4	17.7 ± 8.2
Peak hip flexion	61.7 ± 17.1[b]	50.7 ± 17.4	74.2 ± 14.4	72.7 ± 10.6	51.1 ± 10.6	49.7 ± 9.1	62.3 ± 17	57.7 ± 16.6
Peak hip extension	5.30 ± 3.30	11.2 ± 11.2	6.80 ± 5.20	9.20 ± 4.10	2.90 ± 7.20	9.9 ± 5.10	5.02 ± 5.6	10.1 ± 7.2[a]
Peak hip external rotation	16.04 ± 6.4	14.9 ± 6.80	18.5 ± 7.80	19.3 ± 8.90	19.99 ± 7.2	20.7 ± 6.8	18.2 ± 7.2	18.3 ± 7.8

[a] Indicates difference between sexes ($P < .05$).
[b] Indicates sex-by-task interaction ($P < .05$).

Table 2. Root-Mean-Square Electromyographic Activation Levels for the Eccentric Phase of Exercise (Mean ± SD)

Muscle	Exercise						Grand Mean for All Exercises, %	
	Single-Leg Squat, %		Lunge, %		Step Up and Over, %			
	Men	Women	Men	Women	Men	Women	Men	Women
Gluteus maximus	16.8 ± 14	29.7 ± 19.2[a]	13.7 ± 9.5	27.6 ± 16.9[a]	10.4 ± 9	17.6 ± 11.3	13.6 ± 12.5	24.9 ± 12.7
Rectus femoris	21 ± 12.1	30.8 ± 19.7	11.7 ± 6.9	23.9 ± 15.7	6.5 ± 3.4	15.1 ± 20.6	13.03 ± 11.3	23.3 ± 11.5[b]
Adductor longus	17.5 ± 7.5	19.2 ± 12.1	12.5 ± 7.5	21 ± 17.9	16.2 ± 10.4	20 ± 18.6	15.4 ± 11.5	20 ± 11.5
Dominant gluteus medius	25.3 ± 11.5	26.6 ± 6.8	15.5 ± 9	17.8 ± 8.8	14.4 ± 9.6	14.5 ± 4.6	18.4 ± 7.7	19.7 ± 7.8
Nondominant gluteus medius	10.6 ± 5.8	12.6 ± 9	14.8 ± 4.7	20.8 ± 15.9	13.3 ± 4.6	18.7 ± 14.3	12.9 ± 8.7	17.4 ± 8.9

[a] Indicates sex-by-task interaction ($P < .01$).
[b] Indicates difference between sexes ($P < .05$).

Gluteus Maximus. We found a sex-by-task interaction during the eccentric phase of the gluteus maximus ($F_{1,2} = 3.5$, $P = .03$) but not during the concentric phase ($F_{1,2} = 2.4$, $P = .13$). Post hoc testing revealed that, although women demonstrated greater activation during all 3 tasks compared with men (single-leg squat: 29.7% ± 19.2% versus 16.8% ± 14%, respectively; lunge: 27.6% ± 16.9% versus 13.7% ± 9.5%, respectively; and step up and over: 17.6% ± 11.3% versus 10.4% ± 9%, respectively), this was only different during the single-leg squat ($P = .02$) and lunge ($P = .002$). In addition, women demonstrated greater average RMS amplitudes during the lunge than during the step up and over (27.6% ± 16.9% versus 17.6% ± 11.3%, respectively; $P \leq .001$) and during the single-leg squat than during the step up and over (29.7% ± 19.2% versus 17.6% ± 11.3%, respectively; $P \leq .001$), whereas men demonstrated greater RMS amplitudes during the single-leg squat when compared with the step up and over (16.8% ± 14% versus 10.4% ± 9%; $P = .004$).

We found a main effect for sex for the eccentric ($F_{1,2} = 8.5$, $P = .006$) and concentric ($F_{1,2} = 5.7$, $P = .02$) phases. Average RMS amplitudes for gluteus maximus were greater for women (31% ± 15.7%) than for men (19.6% ± 15.4%) across all exercises for concentric phases.

Rectus Femoris. We found a main effect for sex for both eccentric ($F_{1,2} = 8.5$, $P = .006$) and concentric ($F_{1,2} = 4.99$, $P = .03$) phases. Average RMS amplitudes for the rectus femoris were greater for women than for men for the eccentric (23.3% ± 11.5% versus 13.03% ± 11.3%, respectively) and concentric (16.3% ± 9.6% versus 9.8% ± 9.4%, respectively) phases across all exercises. We did not find a sex-by-task interaction for either the eccentric phase ($F_{1,2} = 0.32$, $P = .7$) or the concentric phase ($F_{1,2} = 1.3$, $P = .27$).

Adductor Longus. We did not find differences between sexes for the eccentric ($F_{1,2} = 1.7$, $P = .20$) or concentric ($F_{1,2} = 1.9$, $P = .17$) phase of the adductor longus muscle during any of the exercises. In addition, we did not find a sex-by-task interaction for the eccentric ($F_{1,2} = 2.2$, $P = .12$) or concentric ($F_{1,2} = 3.3$, $P = .08$) phase.

Dominant-Limb's Gluteus Medius. We did not find differences between sexes for the eccentric ($F_{1,2} = 0.29$, $P = .56$) or concentric ($F_{1,2} = .02$, $P = .88$) phase of the dominant limb's gluteus medius muscle during any of the exercises. In addition, we did not find a sex-by-task interaction for the eccentric ($F_{1,2} = 0.59$, $P = .56$) or concentric ($F_{1,2} = 0.92$, $P = .4$) phase.

Nondominant-Limb's Gluteus Medius. We did not find differences between sexes for the eccentric ($F_{1,2} = 2.7$, $P = .11$) or concentric ($F_{1,2} = 2.7$, $P = .11$) phase of the nondominant limb's gluteus medius muscle during any of the exercises. We also did not find a sex-by-task interaction for the eccentric ($F_{1,2} = 1.6$, $P = .2$) or concentric ($F_{1,2} = 2.7$, $P = .07$) phase.

DISCUSSION

The purpose of our study was to determine if lower extremity 3-dimensional kinematics and hip muscle EMG activation differed between men and women performing CKC rehabilitation exercises. Knowledge of potential sex differences for uninjured participants provides better comparisons when interpreting data after injury or surgery. Our results demonstrated that women moved into smaller degrees of knee flexion and larger degrees of hip extension angles when compared with men across all exercises. Women also moved into smaller degrees of hip flexion during the single-leg squat when compared with men. Women demonstrated increased activation levels of the rectus femoris and gluteus maximus muscles compared with men across all exercises.

We believe the sex differences in peak knee and hip joint angles observed in our study may have resulted from strength differences between the 2 groups. Although we did

Table 3. Root-Mean-Square Electromyographic Activation Levels for the Concentric Phase of Exercise (Mean ± SD)

Muscle	Exercise						Grand Mean for All Exercises, %	
	Single-Leg Squat, %		Lunge, %		Step Up and Over, %			
	Men	Women	Men	Women	Men	Women	Men	Women
Gluteus maximus	33.9 ± 18.8	51.2 ± 32.1	10.7 ± 9.1	17.6 ± 13.7	14.1 ± 9	24.2 ± 16.3	19.6 ± 15.4	31 ± 15.7[a]
Rectus femoris	16.4 ± 10.3	24.7 ± 16.4	6.2 ± 5.3	8.8 ± 12.4	6.8 ± 3.2	15.5 ± 19.3	9.8 ± 9.4	16.3 ± 9.6[a]
Adductor longus	16.3 ± 8.4	15.2 ± 8.2	8.1 ± 5.1	19.5 ± 28.5	15.3 ± 6.6	21.9 ± 14.9	13.2 ± 13.2	18.9 ± 13.2
Dominant gluteus medius	31.2 ± 10.9	29.5 ± 7.5	11.6 ± 8.3	11.4 ± 4.8	15.5 ± 7.9	16.5 ± 5.7	19.4 ± 6.6	19.1 ± 6.8
Nondominant gluteus medius	11.6 ± 6.1	12.5 ± 9.3	17.2 ± 7.3	24.6 ± 18.1	14.8 ± 3.8	20.7 ± 14.6	14.5 ± 9.2	19.3 ± 9.4

[a] Indicates difference between sexes ($P < .05$).

not measure strength of the lower extremity muscles, other researchers have shown that males exhibit greater peak isometric and isokinetic strength measures for the hip and knee when compared with females.[18,25,31,32] The men in our study may have exhibited greater overall lower extremity strength, which allowed them to descend into greater degrees of knee flexion during the single-leg squat and lunge when compared with the women.

Our results contradict those reported by Zeller et al.[14] They observed that women descended to smaller degrees of knee and hip flexion when compared with men during the single-leg squat. This difference may result from different participant populations. Zeller et al[14] studied young collegiate athletes, whereas we studied a sample of the population with a more diverse activity level. Therefore, the lower extremity muscle strength of the women in our study may have differed from that of the women in the Zeller et al[14] study, possibly accounting for their inability to squat to similar degrees of knee flexion. Future studies are needed to confirm if females with reduced lower extremity muscle strength move through reduced knee flexion range of motion during the squat.

We did not observe differences between sexes for any of the transverse-plane or frontal-plane motions during any task. These results differ from those of Zeller et al.[14] They observed greater hip and knee frontal-plane and transverse-plane motions between sexes during the single-leg squat. Specifically, women moved into greater degrees of knee valgus and hip adduction and external rotation motion.[14] However, both we and Zeller et al[14] reported peak hip transverse-plane motion occurred in external rotation rather than internal rotation. Hip adduction normally results in internal rotation of the femur, placing the knee in a valgus position.[33] Both we and Zeller et al[14] reported only the peak transverse-plane motion that occurred about the hip joint throughout the 3 exercises, which was into external rotation; however, neither group of investigators examined at what point during the exercise this angle occurred. The timing of peak hip external rotation angle may not have coincided with the occurrence of peak hip adduction and peak knee valgus angle during the task. We will address this in future studies.

The lack of sex differences observed in peak frontal-plane and transverse-plane angles in our study compared with Zeller et al[14] again may result from the different participant populations included. Our population was slightly older and more representative of the general active population; therefore, although we and Zeller et al[14] did not control the depth to which participants were instructed to squat, our population may have been unable to squat to as great a distance as a population of trained athletes. Knee flexion angles were greater in the Zeller et al[14] study (90° for men and 95° for women) than in our study (67° for men and 60° for women) during the single-leg squat. Zeller et al[14] theorized that, as women move into greater degrees of knee flexion during the squat, their hip musculature is less able to control movement into the frontal-plane and transverse-plane motions when compared with men. Neither the male nor female participants in our study squatted to depths equal to the participants in the study by Zeller et al[14] and, thus, those in our study may have placed less demand on the supportive musculature to control the frontal-plane and transverse-plane motions during the squat.

In accordance with our results, Claiborne et al[32] also observed no differences between sexes in peak knee frontal-plane motions during a single-leg squat. Participants in their study were instructed to squat to only a depth of approximately 60° of knee flexion. Sixty degrees and 67° were the average amount of knee flexion observed in our study for women and men, respectively, and the value for women was 35° less than the average that Zeller et al[14] observed for women. Based on these findings, women may lack control of the hip-stabilizing muscles to maintain proper frontal-plane and transverse-plane motion at the knee and hip as knee flexion angle increases during a single-leg squat. Willson et al[25] quantified this relationship, observing a negative relationship between hip external-rotation strength and the degree of frontal-plane motion during a single-leg squat. Based on these findings, the reductions in hip and knee muscle strength observed for women may not affect function until they reach a certain depth of squat, at which point those muscles must work more to control and stabilize the leg during the motion. This suggests that controlling the depth of the single-leg squat to 60° of knee flexion for women initially during rehabilitation may be beneficial for preventing excess motions into the frontal and transverse planes at the knee and hip joints. When the squat can be performed in a controlled manner, the depth of the squat can be gradually increased. However, further study is required before firm clinical recommendations can be made.

Our findings contradicted what previous investigators have reported during explosive tasks, such as landing[22–24] and cutting,[26] in which frontal-plane knee motion increased for females when compared with males. The differences among our studies may result from the differences in the tasks performed. The exercises in our study were more controlled and may not have been as challenging as exercises reported in other studies in which more explosive tasks were employed. Based on these results, we recommend incorporating the 3 exercises examined in our study into CKC rehabilitation programs after lower extremity injury, especially in women, to allow for activation of the hip musculature during functional exercises while limiting excess frontal-plane motion at the knee joint. Employing these exercises before initiating landing or cutting exercises may work to strengthen the muscles that help control these motions and may enable the transition to more explosive exercises to occur in a protected manner.

For mean EMG muscle activation of the 5 muscles examined, we detected sex differences in the gluteus maximus and rectus femoris muscles only during the single-leg squat, lunge, and step-up-and-over exercises. The RMS amplitude of both muscles was greater for women than for men during both the eccentric and concentric phases of the exercises. Zeller et al[14] also observed greater mean RMS EMG amplitude of the rectus femoris muscle for women than for men during a single-leg squat; however, they did not observe any differences for the gluteus maximus muscle when comparing sexes. Their lack of significant findings for this muscle group may have resulted from large SDs observed for this muscle for both men and women. They reported SDs that were one-third of the mean for women and greater than half of the mean for men for the gluteus maximus (81.2% ± 28.9 versus 62.7% ± 43.8, respectively).[14] The inclusion of a greater number of participants in our study may have enabled us to find sex differences. However, although gluteus maximus muscle activity between sexes (18.5%) was not different in their study, it may be clinically relevant. Although we and Zeller et al[14] found sex differences in mean gluteus maximus and rectus femoris muscle activation levels during the single-leg squat, directly comparing the percentages obtained in their study with ours is difficult because they reported the mean maximum muscle activation level for the entire exercise and we reported the mean RMS amplitude for each of the concentric and eccentric phases of each exercise. We believed that dividing the exercises into their eccentric and concentric phases would provide us with a better understanding of the muscle's contribution to the performance of the exercise. However, regardless of the magnitude of activation, women appear to have activated the gluteus maximus and the rectus femoris muscle more during the single-leg squat, lunge, and step-up-and-over exercises when compared with men. As stated, we believe this was the result of strength differences between sexes. If overall muscle strength is reduced in women, it would require greater activation of the muscle to perform the task.[34] Because both of these muscles would be activating to produce movements in the sagittal plane, the increased muscle activity observed for women may have contributed to the reduced peak knee flexion angles when compared with men. Our data suggest that isolating sex is important when examining measures of muscle activation for these 2 muscles.

Interestingly, we and Zeller et al[14] did not report sex differences in activation of the dominant-limb's gluteus medius muscle during any task. In our study, we also did not observe any sex differences for the adductor longus or the nondominant-limb's gluteus medius muscle. The dominant-limb's gluteus medius muscle exhibited activation levels equal to or less than 30% of MVIC for both men and women during all 3 tasks. The nondominant-limb's gluteus medius muscle exhibited activation levels that were less than 20% of MVIC for both men and women during all 3 tasks. The exercises we chose required movements that occurred mostly in the sagittal plane; therefore, it would be expected that the gluteus medius muscles would not be working to produce active movements in the frontal plane during the tasks. Based on the moderate level of activation observed for these muscles, they appear to function as joint stabilizers during these exercises and not as active movers. This finding corresponds with the findings of many authors[35–37] who reported the main function of the gluteus medius muscle was stabilization of the pelvis rather than active abduction of the thigh. Although differences were not observed in an uninjured population, alterations in the activation levels of these muscles may exist in patients after lower extremity injuries. As noted, alterations have been reported for patients with anterior knee pain[9] and chronic ankle instability[13] for the gluteus medius muscle of the injured extremity. The authors of these studies observed prolonged onset times and shorter durations of activity for this muscle, but they did not report mean activation levels. This requires further study in individuals with lower extremity injury to determine if alterations in gluteus medius muscle activation levels exist and to determine the effect possible alterations may have on function.

The exercises we examined did not result in activation levels of any of the 5 muscles above 30% of MVIC (Tables 2 and 3). The activation levels that we observed were less than levels observed by investigators who examined muscle activation levels during more explosive tasks. In comparison, these authors reported average quadriceps muscle activation up to 191% of MVIC during side-step cutting maneuvers[38] and between 45% and 85% of MVIC during a soccer ball kick.[39] Therefore, we recommend incorporating the single-leg squat, lunge, and step-up-and-over exercises in early CKC rehabilitation to make the transition from isolated exercises targeting these muscles to more explosive, demanding exercises for the hip muscles.

Limitations

Our study design and methods had several limitations. We did not control for the speed at which the participants performed the 3 tasks. We chose not to control for this factor so the participants would perform the tasks at their desired speeds, which more closely mimicked a true rehabilitation setting. Therefore, we could not determine the effect that speed had on muscle amplitudes; however, we believe that our results can be generalized to a clinical setting. We did not control the depth to which participants performed the single-leg squat or lunge activities. We normalized lunge distance to leg length but did not limit depth of the squat to provide for the individual variation that would be present in the clinical setting. We chose to standardize the height of the box during the step-up-and-over exercise and did not normalize step height to participant height. Men exhibited greater average height compared with women; however, the difference in average height did not appear to affect movement patterns during the step-up-and-over exercise, as we did not observe greater hip and knee flexion angles for women than for men during this task (knee flexion: 82.5° ± 6.8° versus 83.3° ± 6.70°, respectively; hip flexion: 49.7° ± 9.1° versus 51.1° ± 10.6°, respectively). For knee flexion, we observed a main effect for sex ($P = .02$), but we did not find a sex-by-task interaction ($P = .37$).

CONCLUSIONS

We found differences in lower extremity movement patterns and hip muscle activation levels between men and women during CKC rehabilitation tasks. Hip extension angles were greater and knee flexion angle were smaller for women than for men. Hip flexion angles were smaller for women than for men during the single-leg squat exercise. Muscle activation for the gluteus maximus and rectus femoris muscles was greater for women than for men. Because we observed sex differences, future investigators need to compare the findings for injured participants by sex to garner a better representation of altered kinematic angles and muscle activation levels due to injury. Clinically, incorporating the single-leg squat, lunge, and step-up-and-over exercises in the rehabilitation program for women as a transition from early-phase controlled exercises to late-phase explosive exercises may help them maintain control during the later-phase activities.

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